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MFL TECHNOLOGY FOR DIAGNOSTICS AND PREDICTION OF OBJECT CONDITION

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ABSTRACT

Magnetic Flux Leakage (MFL) technology has been used for NDT of various ferrous steel objects for decades due to its important advantages. The MFL devices usually are intended for NDT of steel wire ropes, tubes, storage tanks, rails etc.
Application of the contemporary instruments and custom software makes it possible to diagnose the object under test condition as like as to predict it in the period ahead. This confirmed by examples from the steel rope, pipeline and storage tank inspections. It is necessary to get and store the large data array from many sensors and then to process it properly for the correct object condition diagnostics. To predict the condition in future it takes to compare the data for a time period. That is why the NDT data collecting just after the object start of operation is very important. Unfortunately, not all regulations and standards demand this and so many owners doesn't do this.

Key words: MFL, diagnostics, steel ropes, pipelines, storage tanks.

Introduction

Magnetic Flux Leakage (MFL) technology is rather usual for NDT of ferrous steel objects now. There are comprehensive bibliography on this. The MFL Compendium published by ASNT in 2010 is one of the examples [1]. The main advantages of this method are:

- High testing efficiency owing to the fact that it is no need to clean the object under test surface from rust, lubricant, grease as like as to remove a protective coating. The testing speed is rather high because of the distance between the magnetic system poles and object's surface (i.e., air gap) may be significant and due to enhanced testing data processing;
- Minimal operator participation;
- High sensitivity to the object's flaws and high accuracy of the object's parameter (e.g., dimensions) measurement;
- The method is very available for automation and computer processing of big data array.

The MFL devices usually are intended for NDT of steel wire ropes, tubes, storage tanks, rails etc. Some of the instrument applications have been known for decades and others, like testing of the prestressed concrete reinforcement, are in development now.
MFL method often grouped together with magnetic particle (MP) method. Both they use similar magnetization systems but are very different in sensors. MFL devices use Hall sensors or sensing coils for flux leakage detecting but MP ones use magnetic particles as indicator of flux leakage.

MFL technology is close to electromagnetic one by principle of operation. If alternating magnetic field is applied to a ferrous object then the magnetic flux through it depends on its geometry, dimensions, magnetic permeability, conductivity and others. The same (excluding conductivity) relates to the MFL technology. Flux leakage arises (or changes) when the object under test has a flaw. The leakage may be detected by sensing coil as like as main flow through the object. Influence of eddy currents inducted in the object leads to a magnetic field displacement to the object surface (skin effect), but in some important cases of applying the influence is not significant because of the object structure. For instance, when steel rope is tested.

Basic Physics

Fig. 1: Magnetic head opened with a rope.

Nevertheless the MFL devices and instruments differs often each other significantly, depending on their purpose and on types of objects under test, all of them bases on the general principle: detection and evaluation of changes in distribution of magnetic flux created in a ferrous object under test by a magnetization system. The changes occur because of the object's section under test irregularity like flaw or dimension change. Thus, magnetic flux leakage arises close to a flaw location in a steel rod or sheet magnetized by U-shape magnetic system with permanent magnet or by electromagnet [2, 3]. Different kind of the magnetizing systems are used. Their configuration and design of a magnetic head depend on the kind of an object under test and its dimensions. Thus the circumferential magnetized system of the magnetic head is used for steel rope NDT [4]. The magnetic head usually consists of two halves which can be located on the rope surrounding it (Fig. 1).

Another configuration of magnetizing system is applied for pipe line NDT. The Pipeline Inspection Gauge (PIG) runs inside a pipe by pressure of a product transported (oil or gas). So its magnetic system consists of the cylindrical magnetic core with magnetic poles on its ends (Fig. 2).

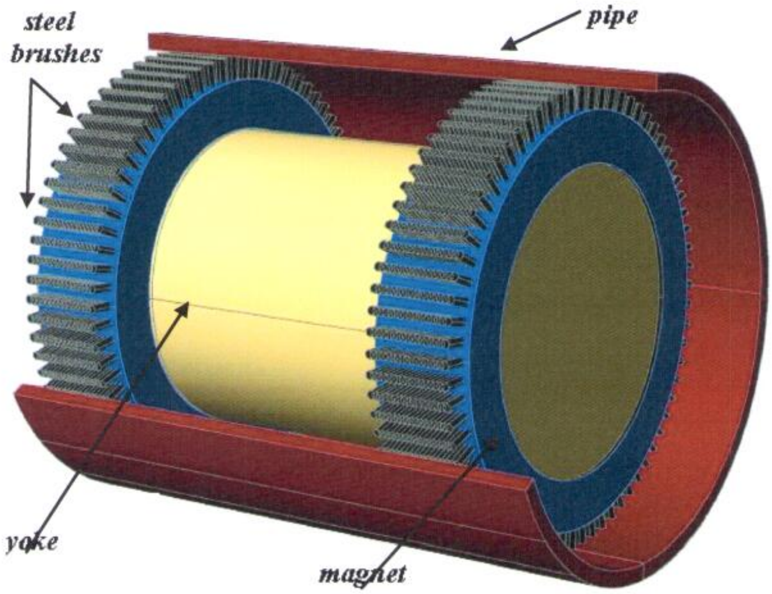

Fig. 2. Diagram of a PIG magnetic system.

The U-shape magnetic yoke is used for steel sheets testing of a storage tanks floor and wall. In any cases Hall sensors or sensing coils located close to the object under test surface detect magnetic flux leakage distortion owing to flaws.
Magnetic saturation of the object section under test is most often used to get the best testing results: high data repeatability, high accuracy and the low limit of sensitivity to flaws [5]. It takes the rather powerful permanent magnets or electromagnets. That is why the MFL devices are rather heavy especially when they intended for NDT of the big cross-section area objects.
The instruments with weak magnetization of the object are lighter. They are used when there are no requirements of high testing data accuracy and low sensitivity limit for flaw detection. In other words, mostly qualitative but no quantitative results are required.
Metrological parameters of the MFL instruments can be rather high. Thus, the measurement error of the steel rope cross-section area loss (LMA) is usually not more than 1% or even less. The sensitivity limits for rope broken wire detection is 1 broken wire (from more than 100 wires) or (0,3-1,0)% of rope cross-section area. The instrument specification including metrological parameters is defined using reference standards, for example rope standards [6] or standards for the MFL storage tank floor NDT [7]. Of course, the real limit of sensitivity can change owing to its dependence on the object's features and testing condition. Inhomogeneity and discontinuity of the object (like magnetic properties change or surface nonuniformity) produce a noise at sensor output. The noise can be produced by object structure, e.g., by the rope strand structure. Changes in the distance between poles of the magnetization system and the object surface as like as the gap between sensor and the surface are one more reason of the noise. The signal to noise ratio defines the limit of sensitivity for flaw. Different methods are used to reduce the sensitivity limit: use of differential sensors, stabilization of the magnetic head position relative to object's surface, magnetic saturation of the object section under test and testing data processing using sophisticated algorithms and powerful software. The last method is more important because it can provide not only the best sensitivity limit and measuring accuracy but also the automation of the objects identification, classification and measuring.

MFL technology of NDT and its capability

The instruments and devices using MFL method are manifold as mentioned above. Here we are considering only that of them which are intended mainly for NDT of the objects in operation. MFL instruments are well known. For instance, the Tubomat System for testing of tube diameter (200-1000) mm. [1; pp.97-105].

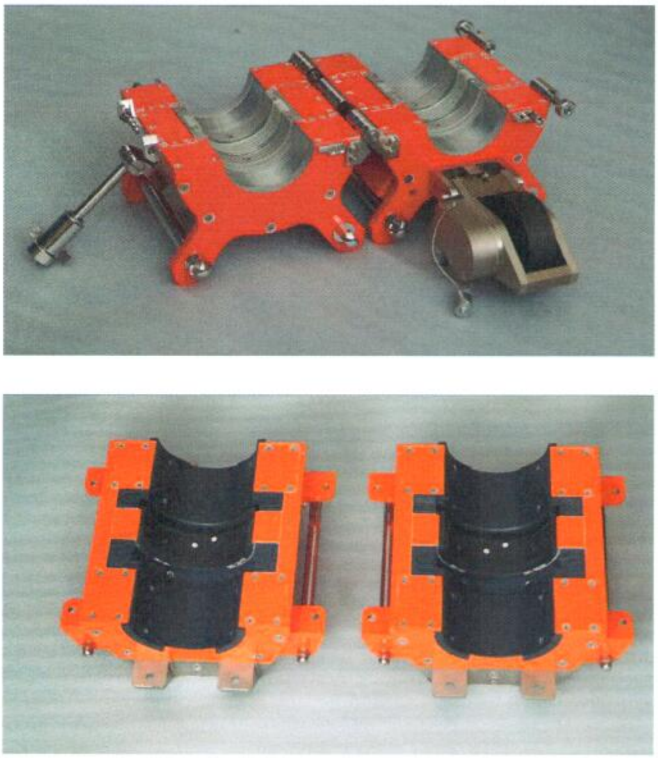

Fig. 3: Magnetic heads opened: on hinges (above) and with separate halves (below).

Elongated steel objects as tubes, rods, rails, wire ropes are typical for MFL NDT. There are many instruments for this. Some other technologies are competitive for the tube, rod and rail NDT. First of all, the ultrasonic testing (UT) is. But for steel wire rope the UT is limited because of the rope complicated structure.

The rope structural design varies on a large scale but all of the rope types are integrated by one feature: they consist of separate wires (or rods) located close each other along a rope axis.

The rope section under test is magnetized along the rope axis by a magnetic head. The magnetic head usually consists of two halves which are clasped the rope under test (Fig. 3).

The rope runs through the magnetic head when tested or the head runs along the rope. The first case corresponds to rope testing at mine hoists, cranes, elevators and other objects with running ropes. The second exists when the rope is fixed: at rope stayed bridges and other constructions, at overhead transmission lines, at some types of cranes, excavators and other machines.

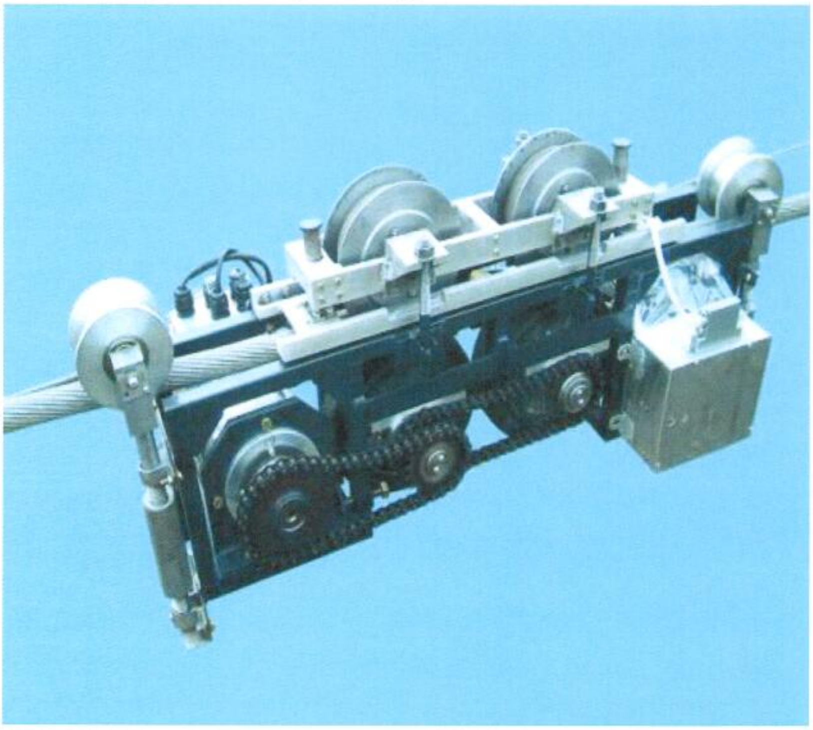

Fig. 4: Free-running machine for a magnetic head move.

The magnetic head is fixed on a construction part in the first case. When the rope is fixed then the head moves along the rope by a pulling rope or by moving part of an installation. In some cases the head moves by a free-running device with an electric drive (Fig. 4). The speed of the rope relative the head is usually from 0,5 to 3-4 m/s but sometimes can reach up to 10 m/s.

Permanent magnets are used most often in the magnetic heads. They can be different form, for instance, as half a disc for each of two heads halves (Fig. 5).

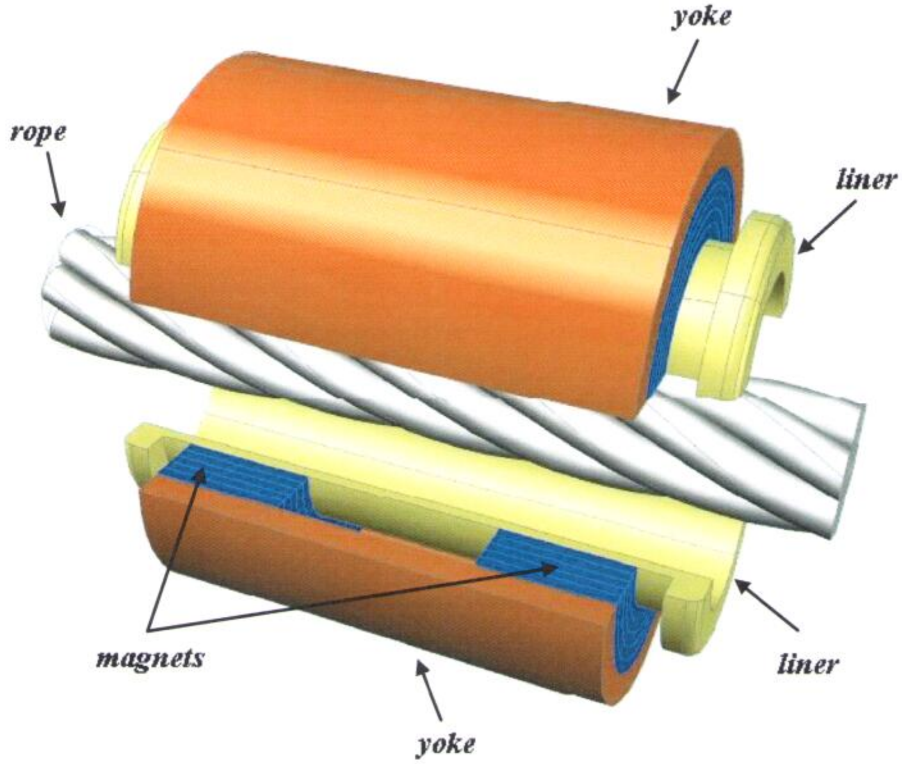

Fig. 5: Diagram of magnetic head for rope testing.

Each half of the disc magnetized radially. Magnetic yoke is tubular and it serves as a head case. Plastic or metal (nonferrous) liners intend to prevent sensor unit and magnets damage by the moving rope.

Centering roller system can be used for this too, especially when the rope speed is high or/and rope diameter is big (Fig. 6).

Fig. 6: Magnetic head with a roller system and a basic unit.

Sensors locate in sensor unit surrounding the rope and generate signals in two channels: loss of metallic area (LMA) and local fault (LF).

Basic electronic unit connected to the magnetic head by a cable, process testing data, displays and stores then using special software. The data can be downloaded to a computer for further processing, storage and displaying.

Steel rope testing by MFL instruments is practically the only NDT method now. Of course, it is used in close combination with visual method. The technology enables to detect so small rope damages as one broken wire (from more than hundred) and measure LMA value with error no more than (0,3-2)% of the nominal rope cross section. The range of the rope under test diameter is (6-150) mm and more.

There are the instrument modifications intended for the continuous rope testing (monitoring). They serve as an automatic mean of rope condition monitoring. The sophisticated software enables to identify rope flaws, to evaluate them and to produce alarm if the rope degradation approaches discard criteria (Fig. 7).

Fig. 7: The INTROS-AUTO instrument for rope condition monitoring:
(a) the magnetic head mounting on the rope;
(b) the electronic unit in a drilling operator compartment.

Another group of instruments using MFL technology consists of scanners for steel tank floor NDT. The instruments for testing of big diameter steel tubes from outside should be attributed to the group too. Their feature is that the magnetic yoke of the instruments is U-shaped because they are put to a flat (or nearly flat) object surface. The number of Hall sensors used varies from 12 up to 256 depending of the scan width.

There are different kinds of the scanners: from the small hand moved ones with scan width (120-150) mm (Fig. 8) up to the automated self-moved ones with scan width (250-300) mm and mapping of the full floor area condition. All of them can inspect floor plate with thickness up to (12-20) mm detecting corrosion damage from 20% of plate thickness. The maximum protective coating thickness – up to 6 mm, the testing speed – up to 0,5 m/s.

Fig. 8: The INTROCOR scanner with scan width 150 mm

There are MFL scanners applicable for tank wall inspection. They can move on a vertical surface manually or as a free-running robot. The MFL scanners are usually used for tank and pressure vessel inspection in aggregate with UT-thickness meter using for the more accurate measure of the damaged plate thickness.

The PIG for oil and gas pipes inspection is, maybe, the most complicate and smart MFL device. A PIG travels inside the pipeline with oil or gas flow and detects magnetic flux leakage created by fractures in the wall. A pipe section under test is magnetized by the PIG's magnetic system using permanent magnets. The systems are different depending on device intention. If the PIG must detect transversal volumetric flaws, the section magnetizes along a pipe; if one need to detect an axial flaw it should magnetize circumferentially. So in the first case the magnetic system represents a cylindrical yoke coaxial with a pipe under test (Fig.2). In the second case the magnetic system consists of a number of U-shaped yokes (with magnets) circumferentially-spaced (Fig. 9). There are the PIGs with combined magnetization [8].

a) b)

Fig. 9: The ROSEN RoCorr.CMFL taken for pipe axial flaw detection: the tool view (a) and the diagram of magnetic flux (b).

Hall sensors are located between yokes poles close to the inner surface of the pipe wall. Their number depends on the pipe under test diameter and can reach up to hundreds. The PIG's dimension and weight can be rather significant: some meters length and more than a tone weight. The inspection speed reaches 5 m/s and the maximum inspection length 800 km. The pipe diameter range (150-1400) mm, the pipe wall thickness range (4-25) mm. Different kind of flaws can be detected and sized when their depth is in range (0,1-0,2) t, where t – the wall thickness.

Huge data array downloaded to computer after inspection is processed by sophisticated software to identify flaw type, to size it, to define its location on the pipe, to display the inspection results and to present a report. To fulfil the work only by operators is impossible practically. It is necessary to collect, to analyze, to store inspection results for evaluation of real pipeline condition. For instance, this work is fulfiled by the DIASCAN company for all Russian oil-trunk pipelines.

MFL technology is very useful by pipe casing NDT of an oilfield borehole. Magnetic system of a tool for this is similar to that of a PIG but uses a direct current magnetization. A cable hoist is used to move the device through the pipe to reliably detect fractures and corroded areas on both the inside and outside surfaces (Fig.10).

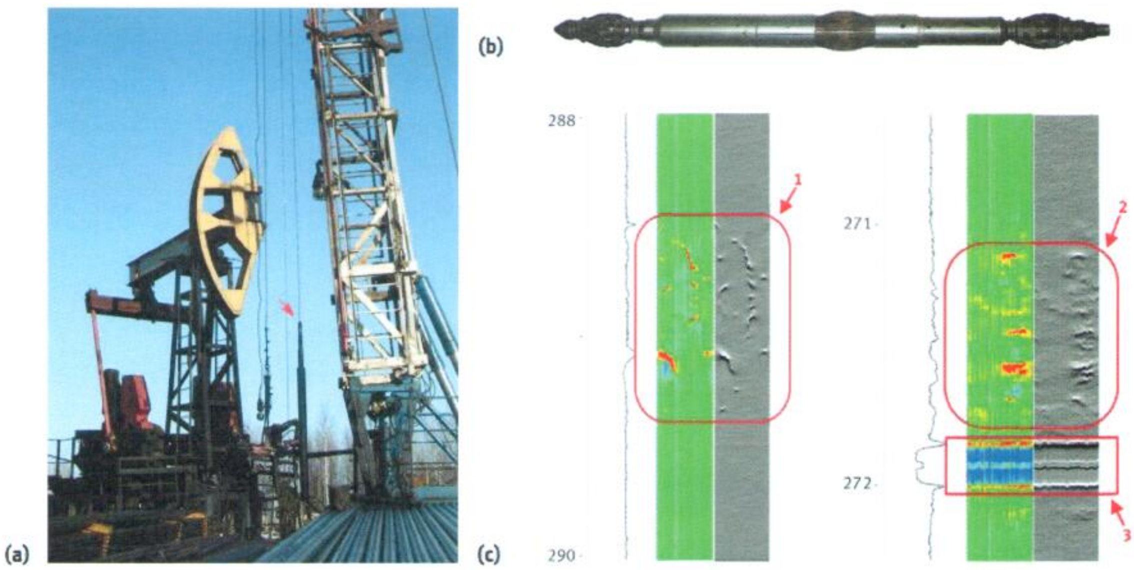

Fig. 10: NDT of an oil well pipe casing by the INTROSCOPE tool (a) the tool (denoted by an arrow); (b) the tool view; (c) data records showing: 1-corrosion damage of casing external surface; 2- corrosion damage of casing internal surface and 3- perforation.

Diagnostics and Prediction of the Object in Service Condition

Real condition of the objects like mentioned above (ropes, tanks, pipes, tubes) in service changes within their lifetime. Evidently that the objects degrade and their safety margin decrease. Existing discard criteria often establish time of service: this approach doesn't take into consideration a difference in service conditions like environment, load intensity and often leads to errors. To avoid the errors, it should evaluate the real condition of the objects. In other words, to diagnose the object condition. To predict the object lifetime, it is necessary to evaluate the object degradation rate.

The NDT technologies can supply us by very important information for an object diagnostics and for degradation rate evaluation. This approach is cited below using an example of the steel rope condition diagnostics and prediction its lifetime.

The working rope situation may be simulated by mechanical strength model of steel wire ropes. Input parameters for the strength model – the measured metallic cross-section loss LMA and number of wire breaks LF – are varying along the rope. This changing is specified by periodically recorded LMA- and LF- charts. In this case one needs to evaluate all the rope structure stiffness parameters for the prescribed distribution of faults using the results of regular inspection. It should be noted that diagnostic parameters LMA and LF are the generalized indexes of degradation. As a matter of fact they are of a random nature and do not account for the distribution of faults over the wires. So the statistical modeling of wear locations in particular rope cross-section is performed and the residual strength parameter is calculated as a probabilistic estimate [9].

The factor of safety is commonly introduced relative to ultimate tensile strength or fatigue strength of wires material (namely, stress safety factor) or relative to tensile strength of the rope as a whole (load safety factor). Let the safety factor $n(t)$ to specify the rope strength at operating time t. It is a minimal value of corresponding parameter $n(x,t)$ that is varying with coordinate x along the rope axis, i.e.

$$n(t) = \min_{x} n(x,t) \tag{1}$$

The duty state of the rope meets a condition

$$n(t) \geq [n]. \tag{2}$$

The allowable safety factor $[n]$ defines the rope's margin of survivability as for partially failed structure. It specifies a reasonable risk when operating the rope with worn-out elements and is called a "vitality" factor in theory of reliability [10]. It may be determined from rope lifetime experiments or estimated regarding the corresponding discard rules.

When condition (2) does not hold, this signifies rope's failure. The rope's near future depends upon answering three questions:

1) Whether to stop or to continue the work of the rope at the achieved operating time t, factoring in recent inspection history?

2) If the decision is to continue, at what operating time should the next examination be conducted and what value for safety factor is then expected?

3) What operating time does it left for the rope just after the last inspection regarding ultimate "vital" factor $[n]$?

To reply one should have a degraded rope safety factor history, which, in turn, is a sequent of NDT history. Real life duration problems have, as a rule, a stochastic nature. But in the absence of individual ropes failure statistics and prior probability assessments of service conditions this study is restricted to deterministic life-time prediction based on the least-square extrapolation of the safety factor changing to the 'vital' limit. Forecasting procedure is adjusted for degradation rate and for proximity of safety factor $n(t)$ to ultimate value $[n]$.

An example of using the NDT data for strength and life-time assessment is demonstrated for cargo crane rope PYTHON 8xK19S+PWRC(K) that has been operating under tension-bending fatigue loading [11]. It was five times examined by magnetic flaw detector INTROS. Rope diameter – 8 mm, sheave diameter – 350 mm, nominal tension – 10 kN, tensile strength of wires – 2160 MPa. The number of loading cycles is considered as an operating time t.

Any noticeable losses of metallic area were not detected. The wire breaks have been revealed only since the third inspection. Processed LF-data were imported to the Rope Strength Software and corresponding distributions of strength estimates over the rope distance were evaluated. The 3[d], 4[th] and 5[th] LF-charts along with the time-quantified strength parameter $n(x,t)$ are shown in Fig. 11.

Local faults indicate the interval where rope failure develops and will probably occur. The minimum values (marked by circles) may be adopted as implicit discard parameters of deteriorated rope. Also they serve as rope state indicators for planning the dates of next inspections and predicting the remaining life-time.

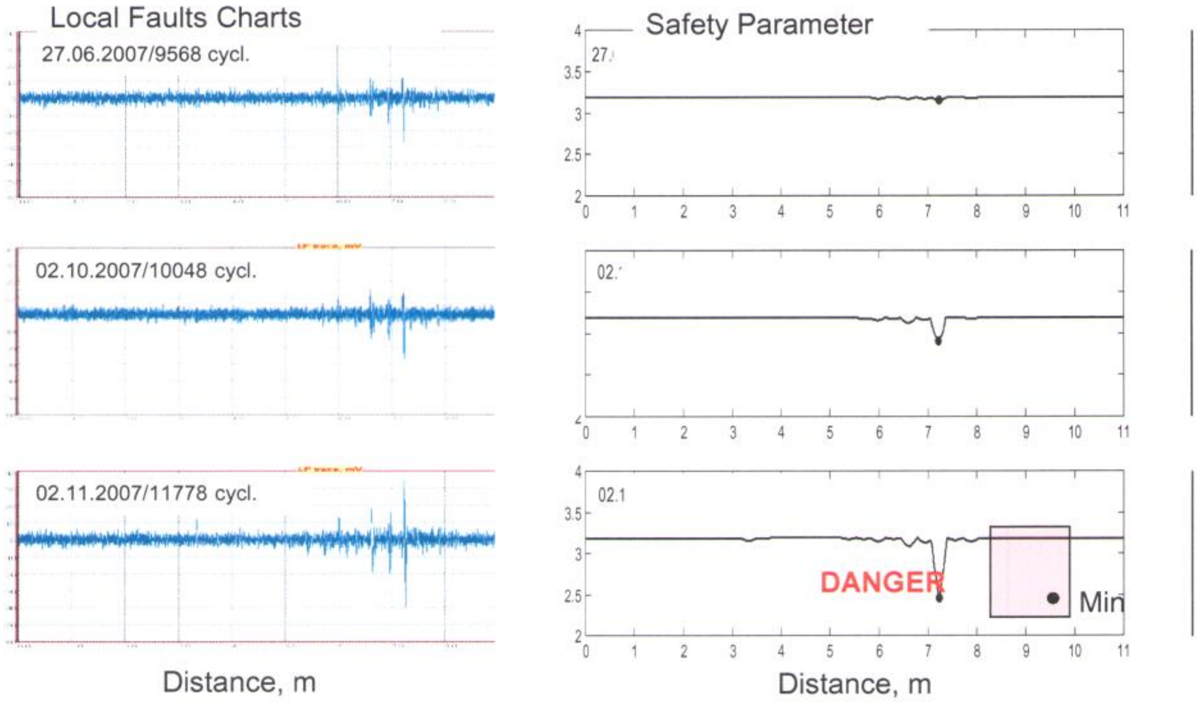

Fig. 11. LF-charts and distributions of crane rope PYTHON D8 strength parameter

Fig. 12 presents the changes in both the minimum estimates treated as safety factors $n(t)$ and expected values for planned inspections as piecewise-linear functions of operating cycles for all NDT history of the rope. The new rope in delivery has the safety factor of 3.2. The allowable level $[n]$ = 1.5 was evaluated with respect to normative LF-standards for rope type under examination. The final planned quantity of operating cycles to the next inspection is equal 13508 with expected safety factor of 1.91.

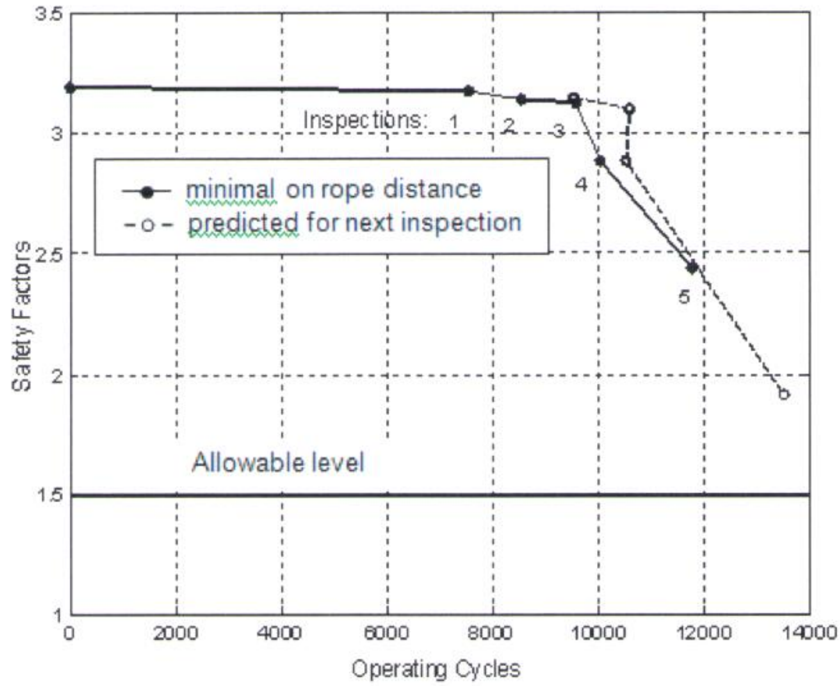

Fig. 12. Safety factors and prospective estimates for crane rope PYTHON D8

Remaining life-time tendency of progressively degraded rope is presented in Fig. 13. Forecasting procedure starts after the second testing when three at least estimates of safety factor are available.. After the last inspection the rope could have reached a defined discard condition of 1.5 in 2850 operating cycles. That rope was not reduced to failure so its real life-time is unknown.

Similar theoretical predictions should be considered purely as a suggestion for the hoisting engine maintenance staff to make the final decision upon the technical state of the rope and what future actions should be undertaken.

The algorithms for the rope safety factor calculation are implemented in the Rope Strength Software [9]. The example cited above shows that to predict an object condition in future it necessary to compare testing data for a time period, at least 3 moments.

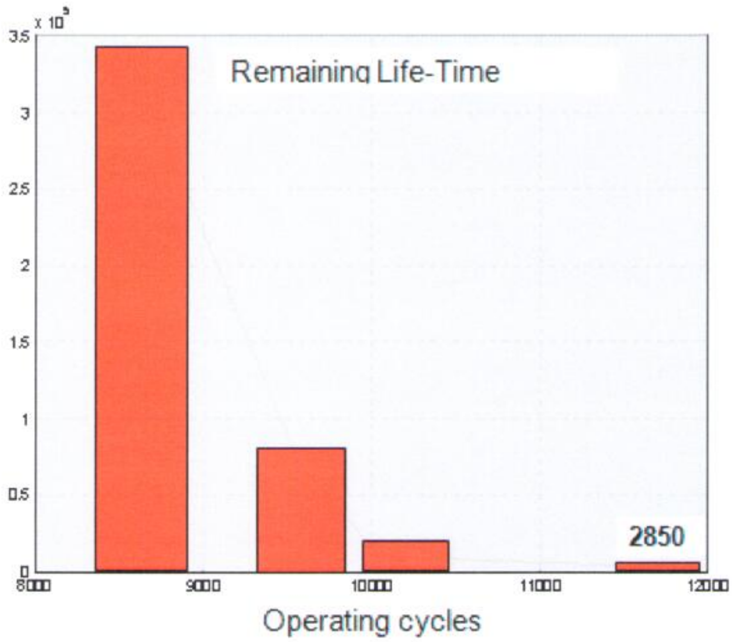

Fig. 13. Remaining life-time estimates for crane rope PYTHON D8

That is why collecting of NDT data just after object start of operation is very important. Unfortunately, not all regulations and standards demand this and therefore many owners of potentially hazardous objects don't do this.

MFL Technology in Operation

Here are some typical examples of the MFL technology use.
The MFL flaw detectors for steel rope inspection have been used extensively through the world for about hundred years. Mine hoist ropes are the most typical objects for them.

Fig. 14: Inspection of a flat steel-rubber rope by the INTROS instrument.

There are instruments not only for haulage ropes of round cross-section but the specialized ones for flat steel and flat steel-rubber balancing ropes (Fig. 14).

Application of the instruments in mining is very cost-effective. For instance, about $130,000 was saved by the Norilsky Nickel company due to life time prolongation of ropes which must be discard according to life time limit criteria [12].

The prolongation was based on testing results obtained at rope NDT by the MFL flow detectors INTROS during 1995-1999. Besides, about $1,000,000 for 5 years is a profit due to:

- increasing of useful working time of a hoist due to inspection time shortening;
- decrease expenses for rope samples cutting off and their destructive testing;
- saving funds for change ropes became too short because of cutting samples off.

Monitoring of rope condition is actual first of all in mining because of hard requirements for safety, high cost of losses at accidents and the significant loss at premature rope discard. It is possible to monitor ropes by ordinary MFL flaw detectors [12]. Testing frequency is increased in this case considerably but a routine procedure is used for testing. To decrease a time loss for the testing, to simplify the procedure and to refuse the skill NDT inspectors, the rope monitor INTROS-AUTO was designed for calf line testing of a drilling rig (Fig.7).
Its features are: rugged design, high usability, simple rope condition indication (signal light), and storage of all the testing data. The instrument magnetic head is installed in the rope under test close to a winch drum and the basic unit located in the drill operator's compartment.
When the signal light on the basic unit indicator is red (or yellow), the operator must (or can) stop the winch and call a rope inspector to check rope condition. The magnetic head is located near the winch drum permanently and can be putted on or taken off the rope at any point.
The sophisticated software was designed to process inspection data to make a decision on rope condition automatically and to store all the data.
It is traditionally to test ropes by MFL instruments at rope ways. There are moving ropes as well stay ropes. Both cases of testing are shown on Fig.15. The requests for NDT are established by national and international rules and practices [13].

a) b)

Fig. 15: Steel rope NDT at rope ways: (a) stay rope; (b) moving rope.

NDT of crane ropes is not so intensive. The MFL flaw detectors are mainly used for rope testing at powerful cranes with high hoisting capacity. Especially, on offshore platforms, in seaports, etc., where the rope diameter is rather big and environment is aggressive (Fig.16).

Fig. 16: Crane rope testing at sea offshore platform.

On the other hand, it is necessary to test ropes at not only such cranes. The rules of safety crane use demand to check ropes if they have no flaws inside the ropes. Evidently, this can be done only by NDT. Unfortunately, the requirement meets not always.

The important area of MFL instruments application is rope inspection of constructions like suspension and rope-stayed bridges, stadium roofs, etc.

Stay rope diameter here is rather large (up to hundred mm) and the diameter of main ropes can reach 300mm. So, to saturate the rope section of such diameter it takes very massive magnetic system.

For instance, the mass of MFL flaw detector for rope with diameter 150 mm is about 200kg including a roller system (Fig. 6).

Pulling rope is pulled by hand or by electric winch (Fig.17). There are magnetic heads adapted for close located stayed ropes (Fig.18).

Fig. 17: Stay ropes testing at bridge: (a) by hand pulling; (b) by winch pulling.

Fig. 18: Magnetic head adopted for close located ropes testing.

Fig. 19: Inspection of an overhead transmission line conductor over a fiord in Norway.

The MFL flaw detectors are used for inspection of the overhead transmission line conductors and guy ropes. A steel rope is used as a core of the conduction. The self moving device, like shown on Fig. 4, moves the flaw detector along the conductor or a swinging platform is used for this (Fig.19). The inspection is actual for the line section crossing rivers or sea firths. MFL scanners are used for the oil steel tank floor inspection because it is corroded intensively due to water and other impurity substance under oil.

The floor is covered by antirust coating like epoxy. So, it needs to remove the coating for UT. That is why the MFL is the main technology for the inspection. It enables to inspect full floor area with rather high speed and without coating removing. But since the measuring accuracy of the scanners is not high, the UT thickness-motors are used for more accurate measure.

Conclusion

The MFL technology is one of the fast developing directions of NDT. It penetrates in new areas of industry and construction more and more due to considerable improvement of the instruments and methods. The technology enables not only to detect faults but to diagnose the object under test condition and predict its future state and life time. It is well enable to automatization and has high-capacity. It is very desirable to intensify the works on creation of codes, rules, practices and other norm documents for the MFL technology application in various areas of industry, transport and construction.

References

[1] The MFL Compendium: Articles on Magnetic Flux Leakage; ASNT, Columbus, OH, USA, 2010, 112.

[2] Weishedel H., The Inspection of Wire Ropes in Service: A Critical Review, Materials Evaluation, Vol.43, # 13, 1985, 1592-1605.

[3] AMOS, D. M. Magnetic Flux Leakage as Applied to Aboveground Storage Tank Floor Inspection, The MFL Compendium, ASNT, Columbus. OH. USA. 2010, 25-27.

[4] Sukhorukov V., Magnetic NDT of Steel Wire Ropes. The 7-th Int. Conference of Slovenian Society for NDT, 24-25 Apr., 1997, Ljubljana, Slovenia, 229-237.

[5] Sukhorukov V., Magnetic Flux Leakage Testing Method: Strong or Weak Magnetization; Materials Evaluation, Vol. 71, 27-31.

[6] ASTM, ASTM E 1571-11: Standard Practice for Electromagnetic Examination of Ferromagnetic Steel Wire Rope, ASTM Book of Standards, Vol.03.03, ASTV International, West Conshohocken, Pennsylvania, 2011.

[7] API Standard 653; Tank Inspection, Repair, Alteration and Reconstruction/API Publishing Services, 1220 L Street, N.W., Washington, DC, 2005

[8] http://roseninspection.net

[9] Volokhovsky V., Vorontsov A., Kagan A. and Sukhorukov V. «Stochastic Assessment of Steel Rope Strength Using Magnetic NDT Results». Experiences with Ropes: OIPEEC Technical Meeting, Lenzburg, 2003, 137-144.

[10] BolotinV.V. Prediction of Service Life for Machines and Structures, ASME Press, NY, 1989.

[11] Vorontsov A., Volokhovsky V., J. Halonen and J. Sunio, Prediction of Operation Time of Steel Wire Ropes Using Magnetic NDT Data. How to Get the Most out of your Ropes, Proceeding of OIPEEC Conference, 11-15 Sept. 2007, Johannensburg, South Africa, 145-154.

[12] Sukhorukov V., Mironenko A. «Monitoring of Mine Hoist Ropes at The Norilsk Nickel Company», Proc. Of Int. Conf., «Mining transport», Szczyrk, Poland, 24-26 Sept, 2003, 111-118.

[13] EN 12927-8: 2004. Safety Requirements for Cable Way Installation Designed to Carry Persons Ropes. Part 8. Magnetic Rope Testing (MRT).